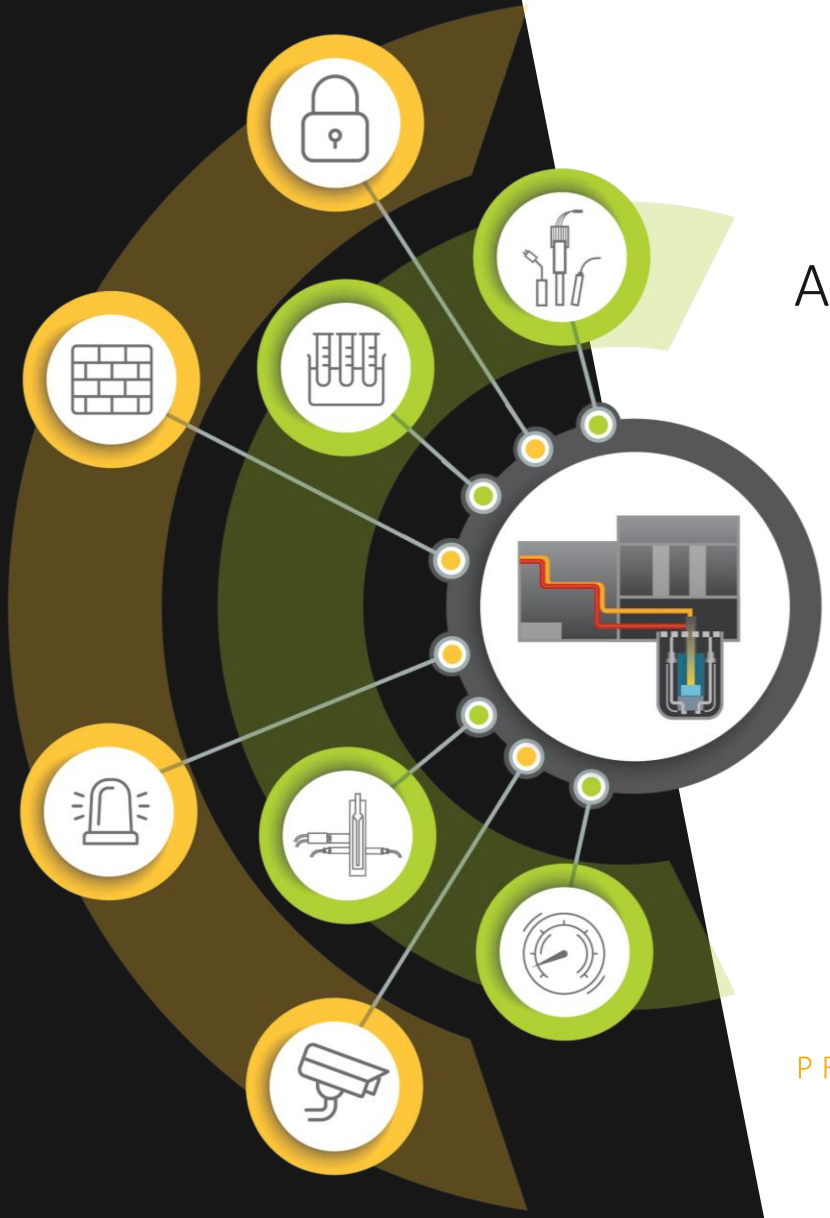

ADVANCED REACTOR SAFEGUARDS

MC&A for Pebble Bed Reactors

May 2024 Program Review - INL

ORNL PUBLICATION ID: 214298

PRESENTED BY

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May 14, 2024

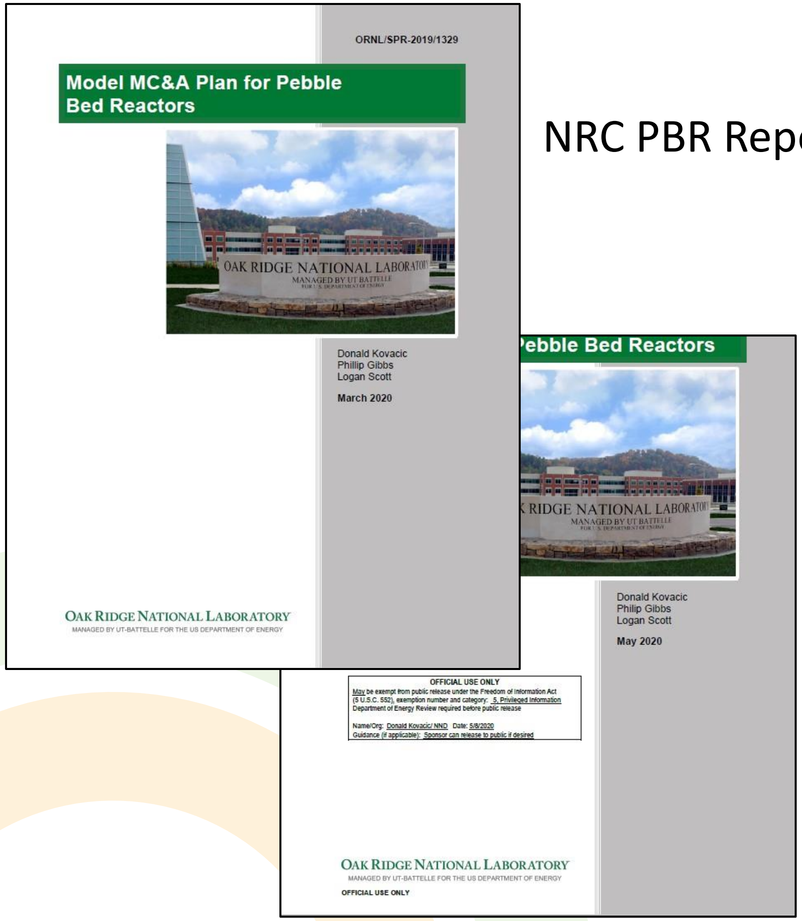
Oak Ridge National Laboratory
Sandia National Laboratories
U.S. Department of Energy

Summary Report on PBR Activities FY23/24

Compile main work done to date on recommended approaches for Pebble Bed Reactor (PBR) Safeguards (M2 Milestone).

- Industry Collaboration
- US NRC MC&A Plan Development
- Reactor Core Modeling
- Material control, transfers, shipments/receipts, and Inventory
- Fresh/Spent fuel measurements
- Statistical approaches
- Reporting / Material Control and Accounting System
- Uncertainty Quantification of Pebble's Discharge Burnup and Isotopic Inventory
- Practical Challenges to Burn Up Measurement Systems
- Micro-Calorimitry measurements at ORNL

ORNL PBR Related Work – 2019-2023



NRC PBR Reports

DOE-NE ARS Reports

Report Recommendations

Industry Collaboration

- X-Energy/ Xe-100 Reactor NDA in place and collaboration since 2020 and now continuing work under ADRP Award.
- Kairos Power – NDA in place and initial collaboration in 2021 and planning to continue under ARDP award

Recommendation 1: Continued engagement between the national laboratories and PBR designers is necessary to put into practice the results and recommendations of this report.

- ol (USNC) pilot TRISO fuel fabrication facility currently operating in Oak Ridge.
  - Support development of MC&A FNMCP for TRISO lines being installed in in Richland WA under a Joint venture with Framatome Fuel Services

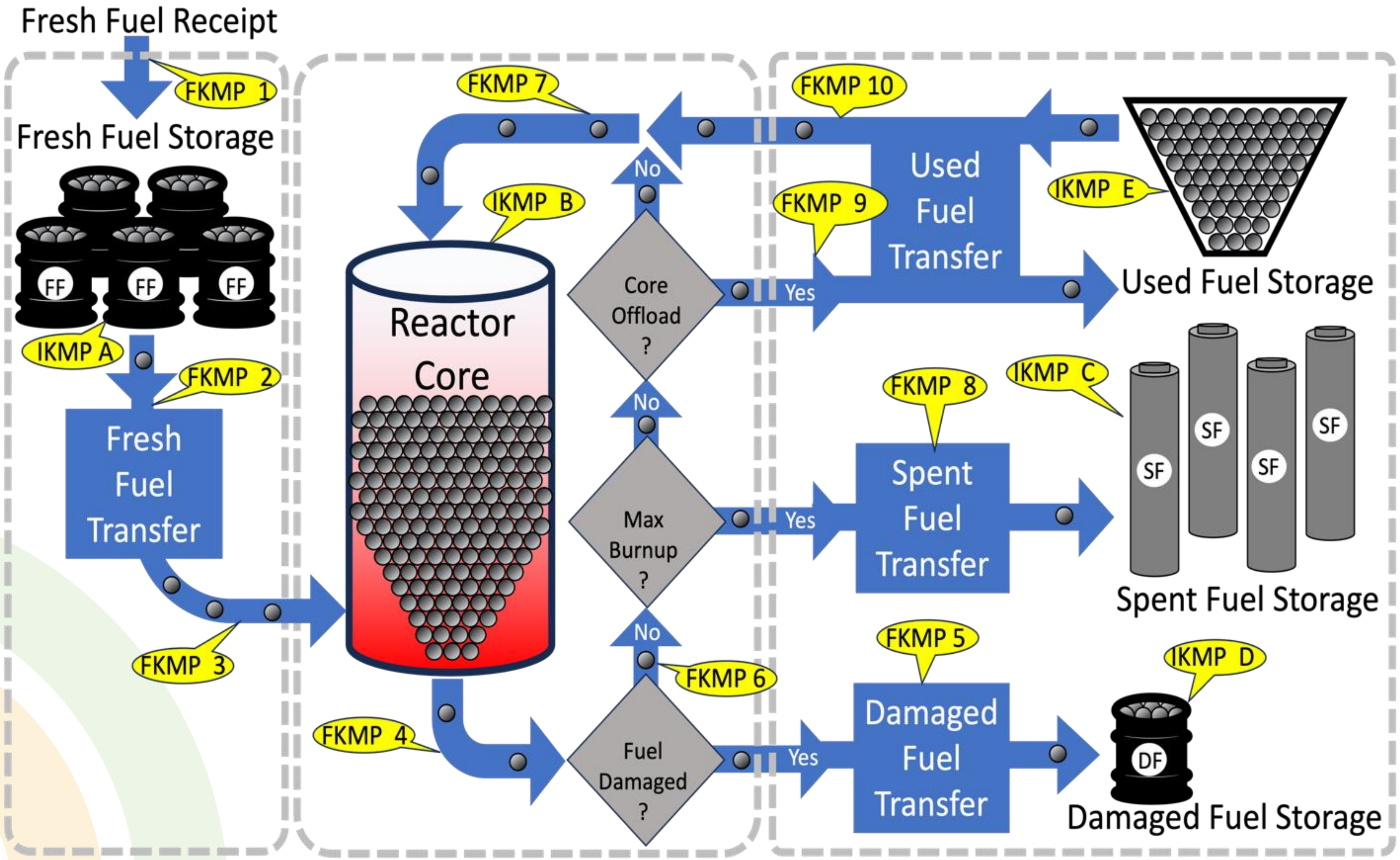
MC&A Plan Development for PBRs

- 10CFR Part 50 provides automatic exception for power reactors for submitting FNMC Plan as part of license
- 10CFR Part 52 does not provide an automatic exception, licensee must request an exception and provide justification
- 10CFR Part 5[illegible] work is not ready for use by applic[illegible]
- Description o[illegible]

Recommendation 2: PBR designers should engage in early, pre-licensing discussions with the NRC to determine an acceptable format for the MC&A plan as part of the overall MC&A program.

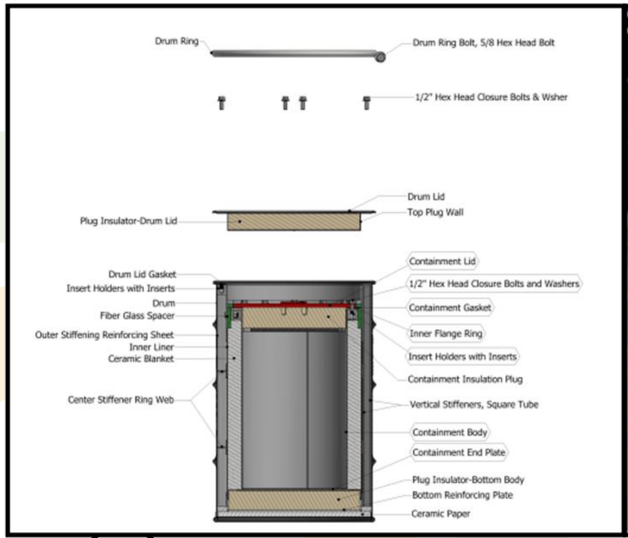
- Unclear if MC&A templates for current NRC LWR licensees will be acceptable and if NRC will approve exemption requests, especially for Category II material (HALEU)
  - Current: Regulatory Guide 5.29 Special Nuclear Material Control and Accounting Systems for Nuclear Power Plants and ANSI N15.8-2009 NMC&A Systems for NPPs
  - Possible NUREG-2159, Acceptable Standard Format and Content for the Material Control and Accounting Plan Required for Special Nuclear Material of Moderate Strategic Significance

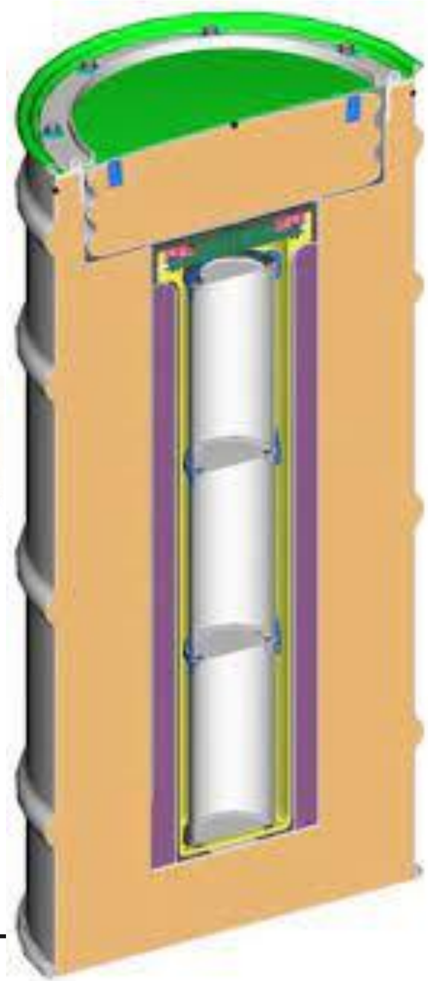
PBR Fuel Flow



Fresh Fuel Packaging and Receipt

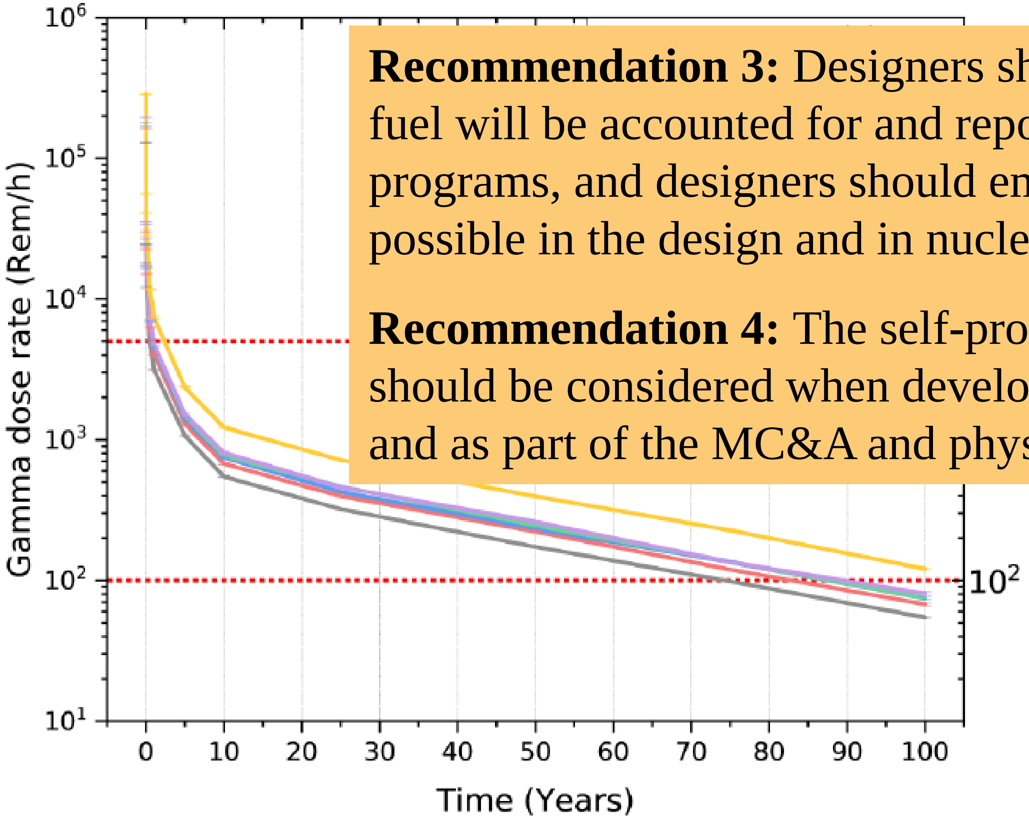
- Work done in FY22 was based on existing packaging concepts.
- Packaging is evolving
- Transportation of fresh HALEU packages are currently being designed and licensed
- Receipt, shipment, transfer, storage, handling, and item monitoring will be straight forward.





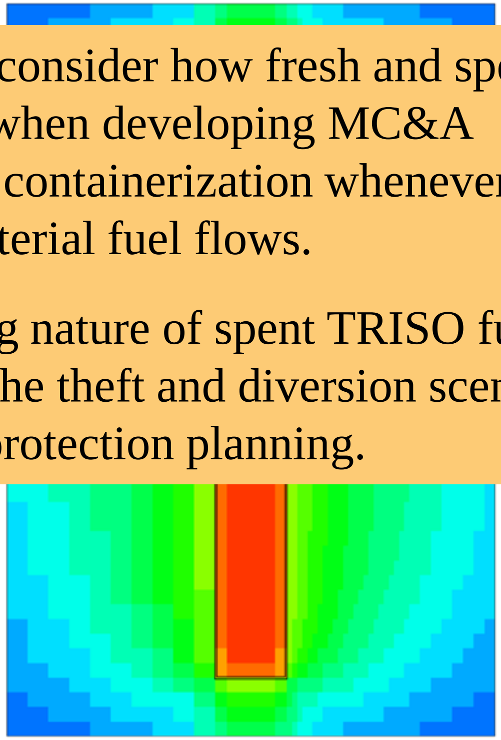
Spent Fuel Cannisters

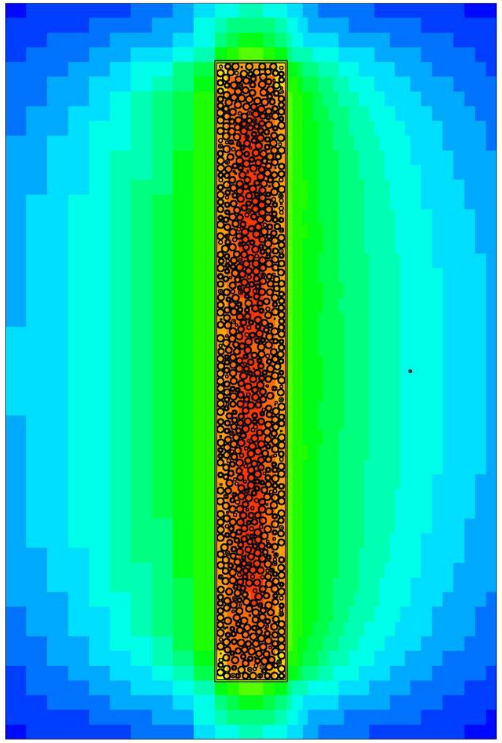
- Design of spent fuel cannisters is ongoing
- Questions regarding wall thickness, height, and diameter will affect measurements
- Dose rate calculations will determine time for self-protection



Recommendation 3: Designers should consider how fresh and spent fuel will be accounted for and reported when developing MC&A programs, and designers should employ containerization whenever possible in the design and in nuclear material fuel flows.

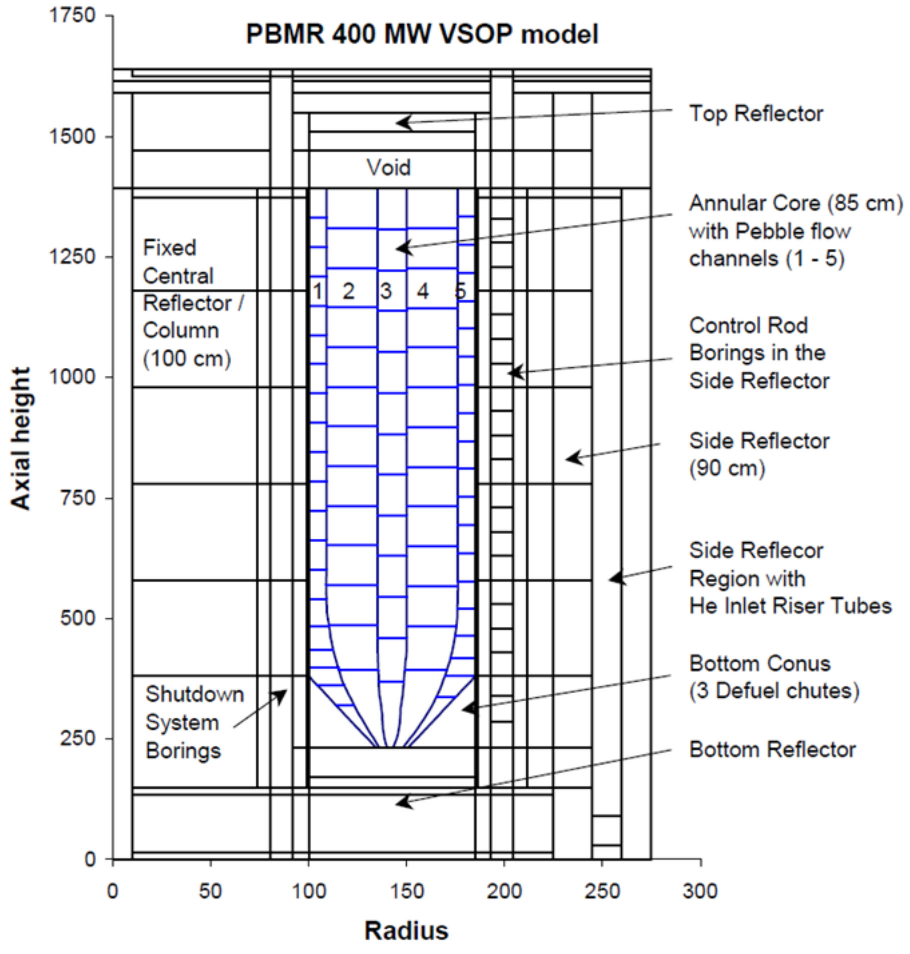
Recommendation 4: The self-protecting nature of spent TRISO fuel should be considered when developing the theft and diversion scenarios and as part of the MC&A and physical protection planning.





Burnup Modeling

- Using PBMR-400 as generic reactor design based on publicly available data using SCALE/ ORIGAMI codes.
- This work is being extrapolated to specific vendor designs as part of NDA and is controlled for IP.
- Reactor core is divided into axial and radial zones to model possible pebble pathways
- Pebbles typically achieve full burnup by the 6th pass.
- Results are then used to
  - Provide actinide isotopics for U/Pu loss and production
  - Develop statistical models for max burnup, target burnup, and decision for when to discharge a pebble
  - Develop synthetic spectra using GADRAS to determine potential gamma signatures for use in BUMS.



SNM Content of a Spent Pebble

Table 1. Comparison of average isotopic mass (mg) per pebble with previous work.

Nuclide	Initial	Retired pebbles	All pebbles after pass 6 (this work)	All pebbles after pass 6 (previous work [21])
^{234}U	7.690	4.8 ± 0.1	4.8 ± 0.1	N/A
^{235}U	864.[illegible]	[illegible]	[illegible]	[illegible]
^{236}U	3.97[illegible]	[illegible]	[illegible]	[illegible]
^{238}U	8,124.[illegible]	[illegible]	[illegible]	[illegible]
Total U	9,00[illegible]	[illegible]	[illegible]	[illegible]
^{238}Pu	0	[illegible]	[illegible]	[illegible]
^{239}Pu	0	[illegible]	[illegible]	[illegible]
^{240}Pu	0	[illegible]	[illegible]	[illegible]
^{241}Pu	0	19.3 ± 1.5	19.7 ± 1.1	28 ± 4
^{242}Pu	0	14.6 ± 1.6	19.4 ± 1.5	20 ± 2
Total Pu	0	123.9 ± 6.5	125.9 ± 4.6	137.8 ± 10.5

Estimate U and Pu inventories in an APR-1400 spent fuel assembly

Isotope	Inventory (kg)
U total	397.2
^{234}U	0.071
[illegible]	2.61
[illegible]	2.44
[illegible]	392.0
[illegible]	4.45
[illegible]	0.16
[illegible]	2.60
^{240}Pu	1.30
^{241}Pu	0.73
^{242}Pu	0.43

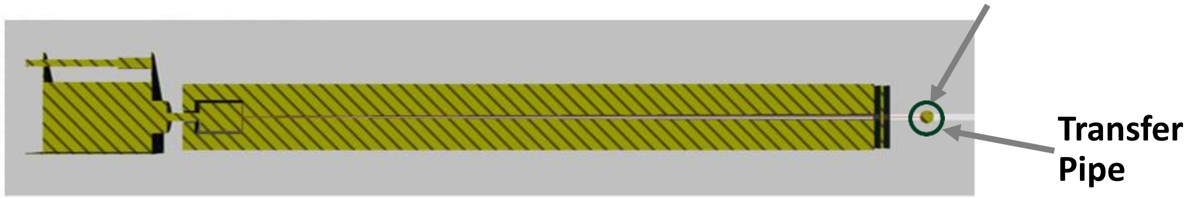
Recommendation 5: Models should be developed for each design to adequately represent the production and loss of nuclear material based on the specific features and operations of the reactor.

Assuming 2000 pebbles in spent fuel container = 0.276 kg

Burn-Up Measurements

- Burn-up measurement systems quantify one or more aspects of irradiated nuclear fuel in support of
  - Process Control
    - For the pebble bed reactors the burn-up monitors will be used to determine if a pebble has reached sufficiently high burn-up that it should be removed from the core.
    - For each pebble how many passes had is made through the core.
  - Nuclear Material Control and Accountability (NMC&A)
    - U and/or Pu mass content
  - International Safeguards
    - Is the reactor being operated as declared?

A simplified gamma-ray detection arrangement for irradiate pebbles.



NDA Measurements - Gamma

- BUMS will rely on gamma signatures
- GADRAS synthetic spectra evaluated potential signatures of pebbles
- 100 hours cooling time
- Cs137 absolute quantity is a good indicator of burnup

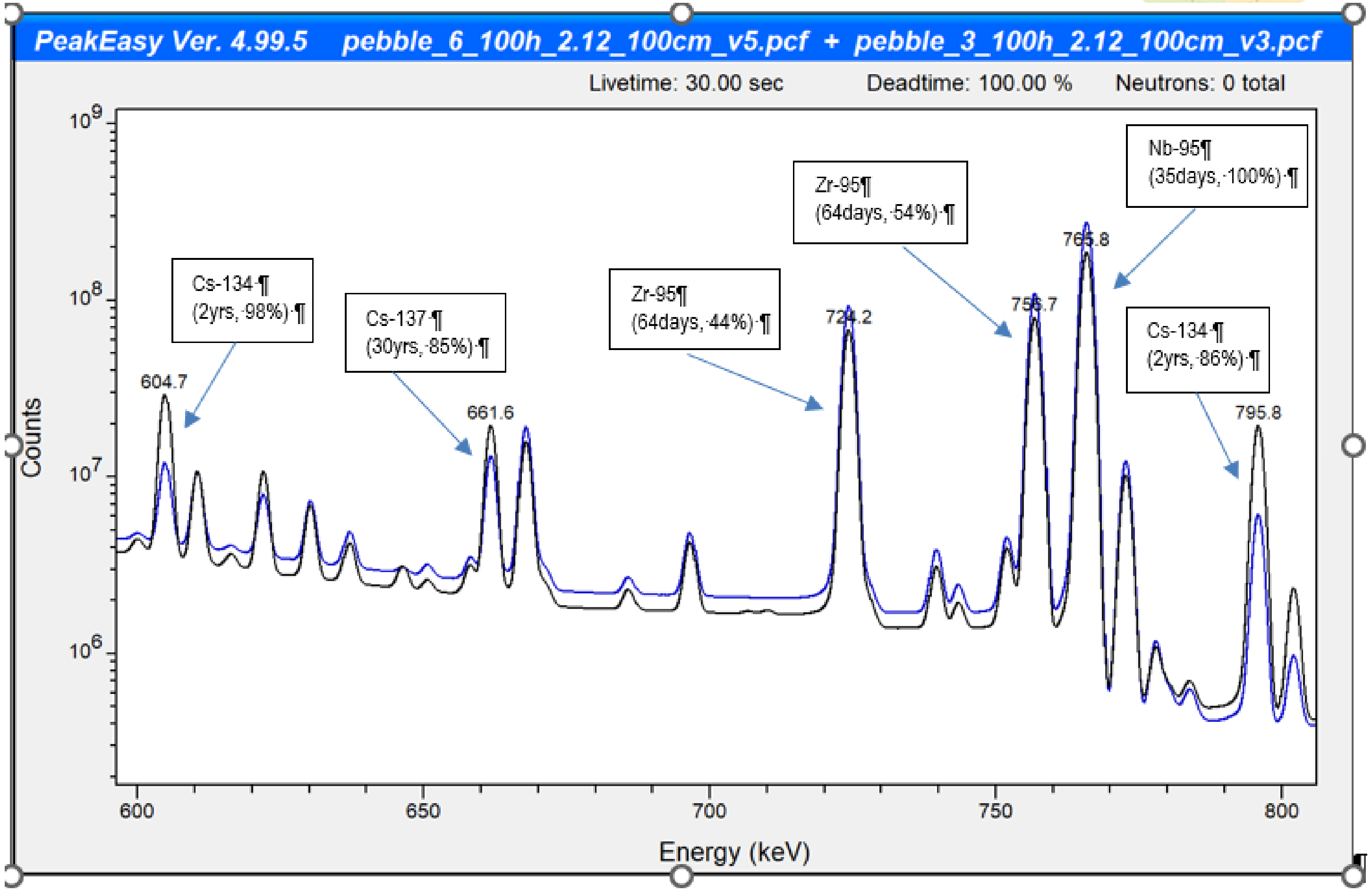


Figure 20. Close-up of the synthetic HPGe gamma spectra generated by GADRAS for Pebble 3 (blue) and Pebble 6 (black) in the energy range of 600–800 keV with the prominent gamma lines labeled. The labels include the primary emitter, its half-life, and the branching ratio (in percentage) of the respective gamma line.

Burn-Up Measurement Systems

- Challenges for Pebble Burn-up monitors
  - Short cooling times ~ 100 hours
    - Normally burn-up measurements are made years after removal from the core
    - Exposure rates are very high and variable over the course of the measurement window. The isotopic ratios vary by the hour in this short time regime.
  - Low mass: 2 to 7 grams SNM/pebble
    - Normally burn-up measurements are performed on a fuel rod or fuel assembly (100's of grams SNM).
    - Differences from pass to pass are small.
  - High ambient background levels in measurement area
    - Impact on measurement performance.
    - Impact on detector lifetime.
  - Throughput requirement is very high
    - 10's of thousands of Pebbles ➔<60 seconds/pebble

Gamma System: Impact of High Radiation Environment

- Fission product loading of irradiated pebbles produces exposure rates in excess 100 R/hr while typical HPGe detectors saturate at 2.5 mR/hr
  - requiring large stand-off distances (several meters)
- Significant shielding and tight collimation are required to mitigate the high background levels from the operating reactor.
  - Shield thickness: >15 cm Pb or W
  - Tight collimation: <0.0002 steradians (complicating detector alignment)
- High neutron backgrounds limit detector lifetime
  - A HPGe typical detector tolerates an integrated fluence of ~1E9 n/cm^2
  - Neutron damage degrades detector resolution adversely impacting measurement precision and due to the complexity of the spectra will introduce measurement bias.
  - Fast neutron fluences in excess of 100 n/s (5-10 mR/h) can render a detector useless in less than 4 months.
  - Neutron shielding will be required to provide a useful detector lifetime.

BUMS Design Needs

- Identify suitable measurement method
  - Optimize performance for the selected signatures
  - Ruggedize measurement system for extreme environmental and radiometric conditions (it will be hot both radiometrically and thermally)
    - Detection mechanism will have to be operated from a remote location.
  - Ruggedize for industrial environment (noise/vibration/humidity/dust etc).

- Potential performance explored through simulations.

Recommendation 6: Work should continue to develop gamma measurement systems in collaboration with the national laboratories, vendors, and measurement equipment manufacturers.

BUMS: Neutron Detection

- Passive neutron detection
  - Benefits:
    - Potentially more sensitive to burn-up than gamma-spectroscopy
    - Simple, reliable

Recommendation 7: Passive neutron detectors should be explored to see if they can either perform better than gamma detectors or if they can complement gamma detectors for MC&A purposes. They may also be considered as confirmatory measurements for retired pebbles as they exit the reactor system before being placed in spent pebble storage canisters.

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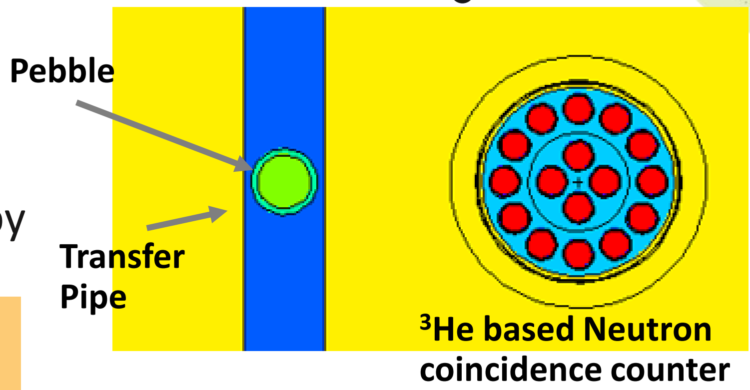
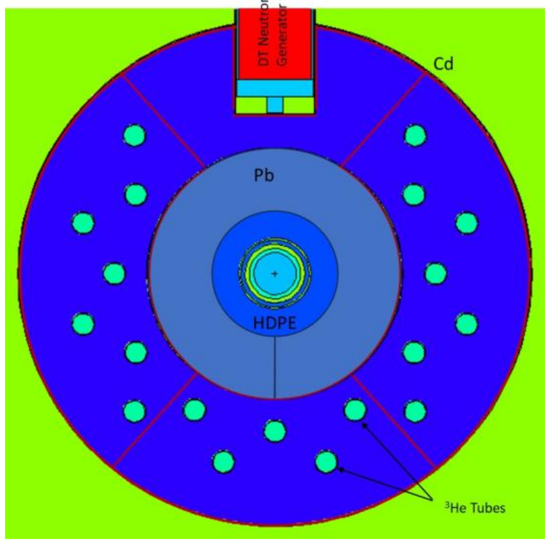
Passive neutron detection system



Active neutron detection system

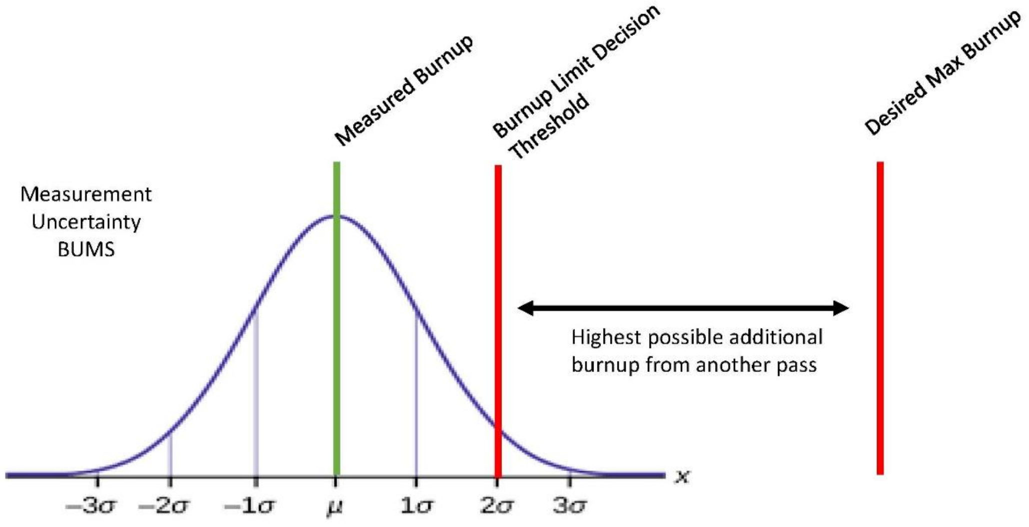


Statistical Approaches for PBRs

1. Burnup measurement discharge decision
2. Burnup measurement versus reactor code comparison
3. Analysis of Variance (ANOVA) between reactors

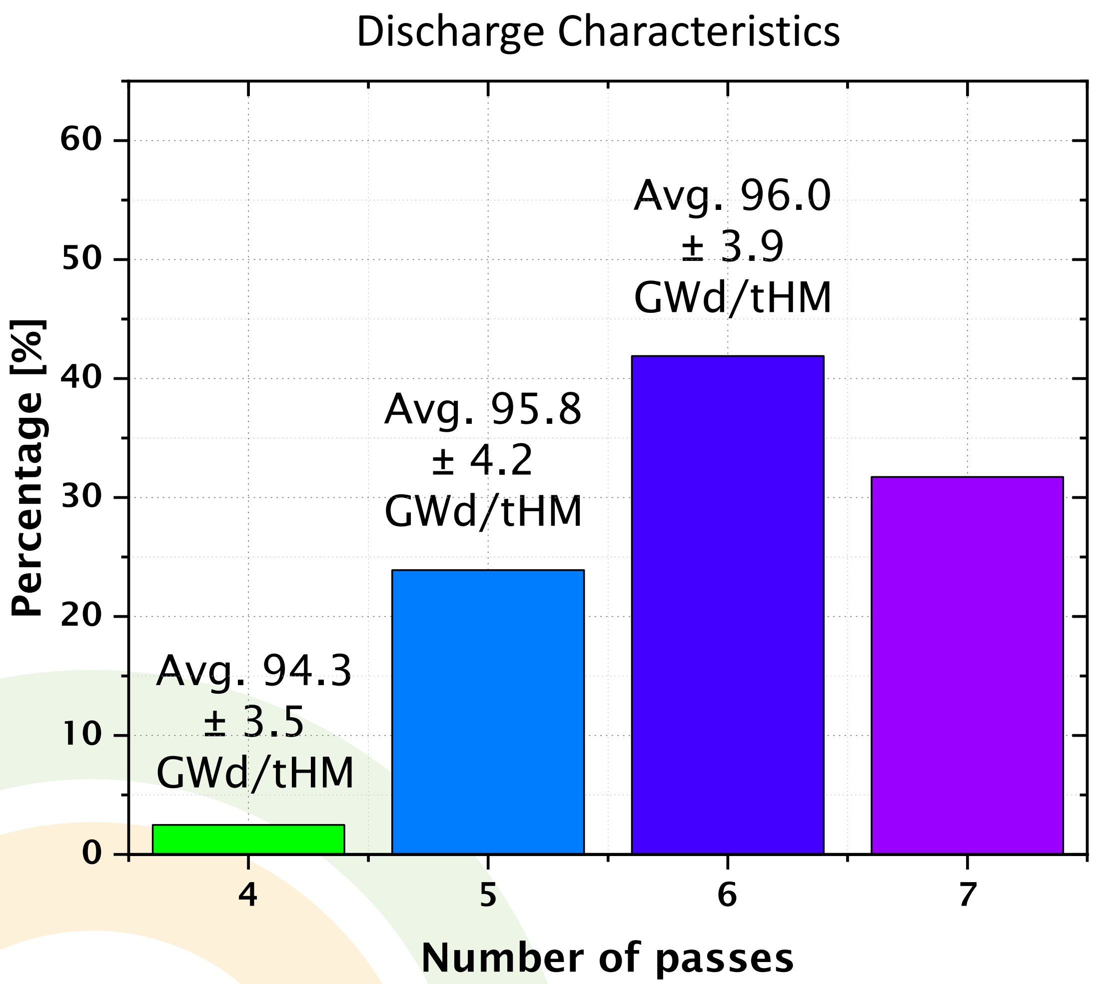
Statistical Approach

- Decision to "retire" (discharge) a pebble based on measured burnup values by BUMS
- Pebble should be discharged at optimal time before exceeding maximum allowable burnup based on the highest energy path that might be taken
- Burnup measurement and model uncertainties must be considered.

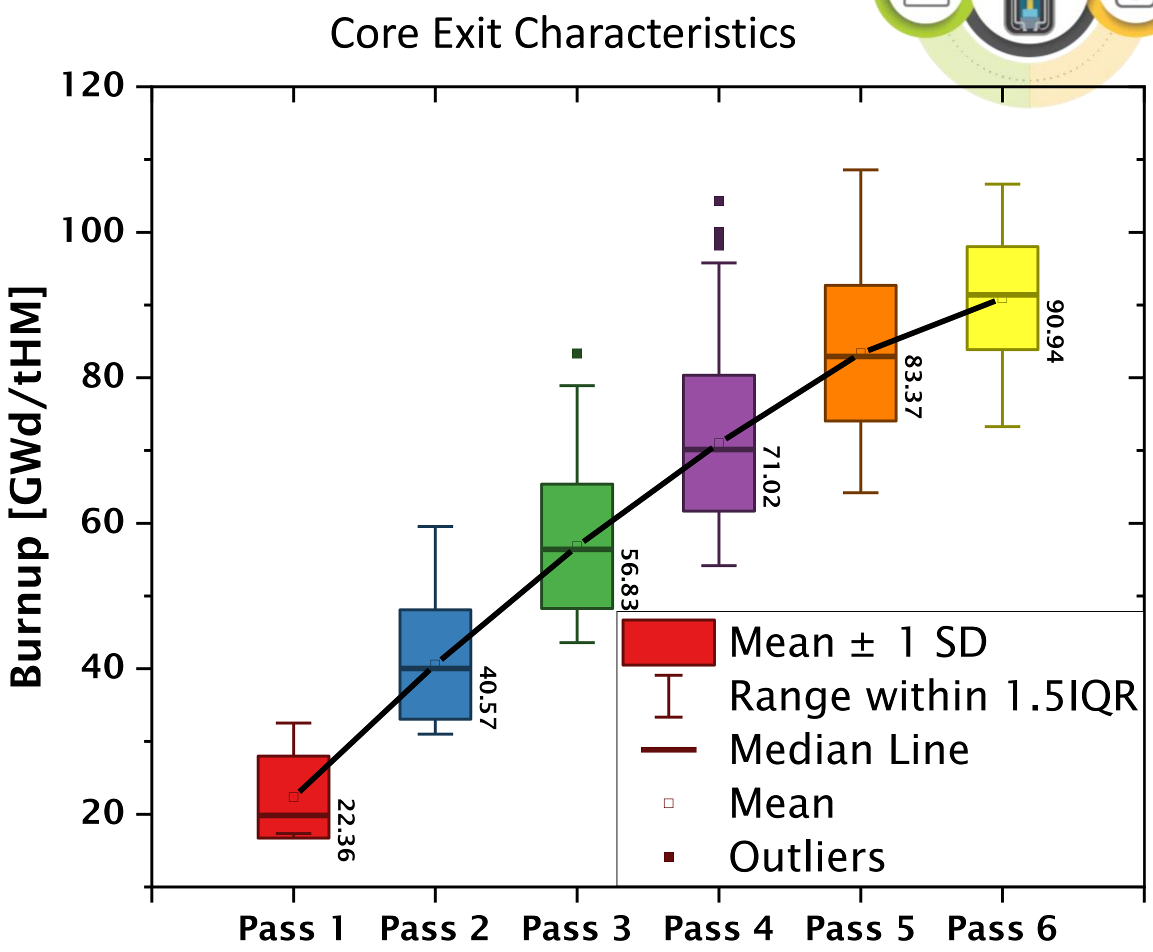


- Type I error—Discharging a pebble when it should have been returned to the reactor, resulting in underutilized fuel **(false positive).**
- Type II error—Returning a pebble to the reactor when it should have been discharged, resulting in a pebble exceeding the maximum desired burnup and creating possible safety concerns and/or less-than-desirable operational performance **(false negative).**

Burnup Measurement Discharge Decision



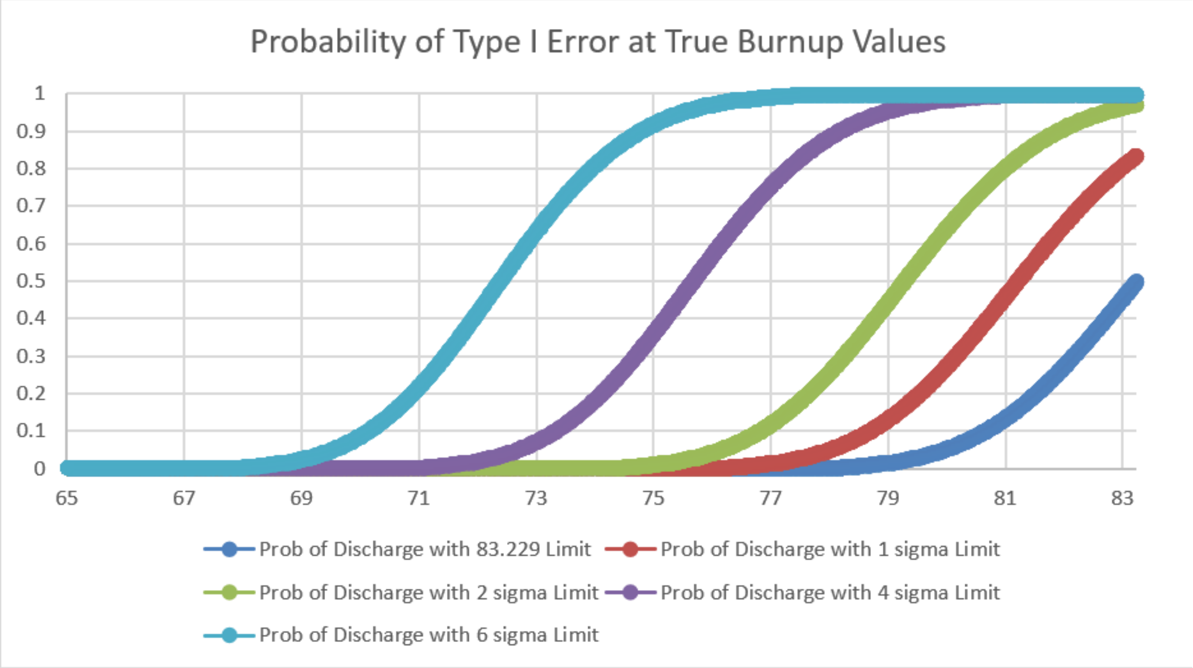
Target discharge burnup is 90 GWd/MTU achieved for about 65% of pebbles in 6 passes.

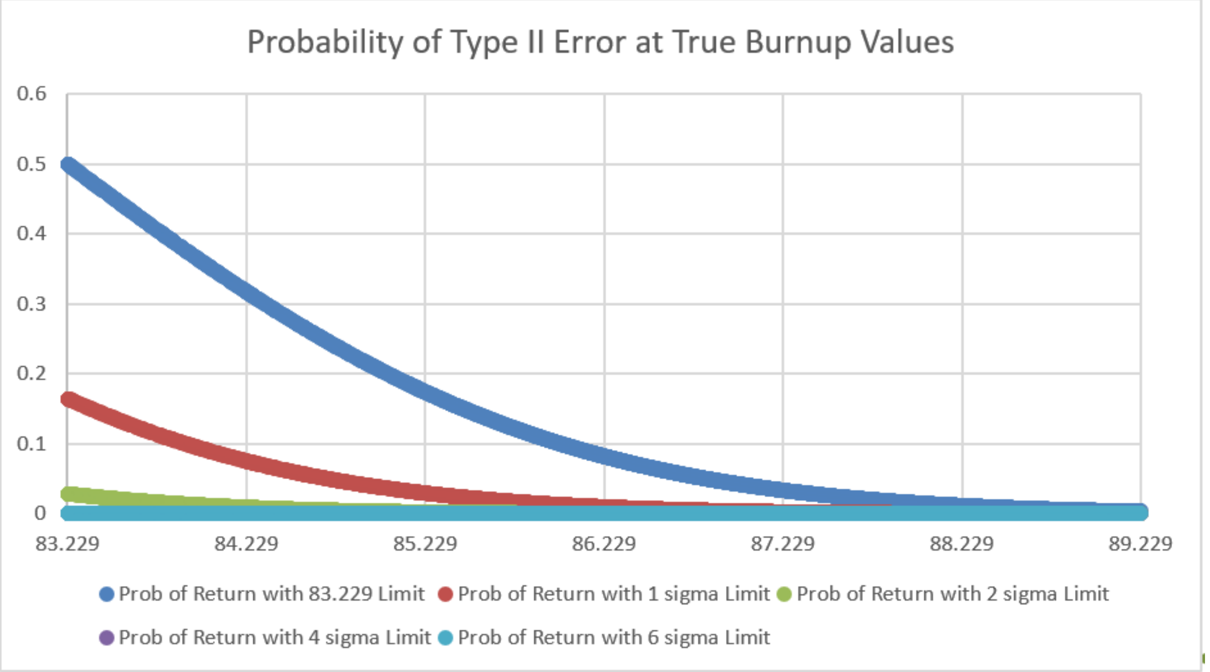


Outliers are those pebbles outside of the 1.5 Inter-Quartile Range (IQR). For a normal distribution, this would be outside approx. +/- 3σ.

Type I vs. Type II Errors

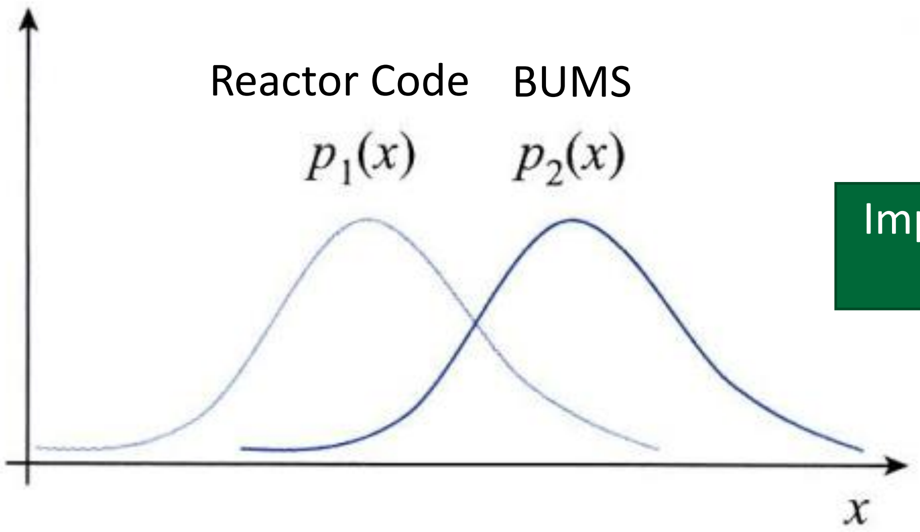
- Highly conservative measurement bounds results in Type I errors – **premature retirements**
- However, results in high safety margin – very few “**overburned” pebbles**
- Non-conservative bounds maximize fuel performance but may result in increased overburned pebbles
- **Operators must decide the balance – 1, 2, 4, 6 σ**





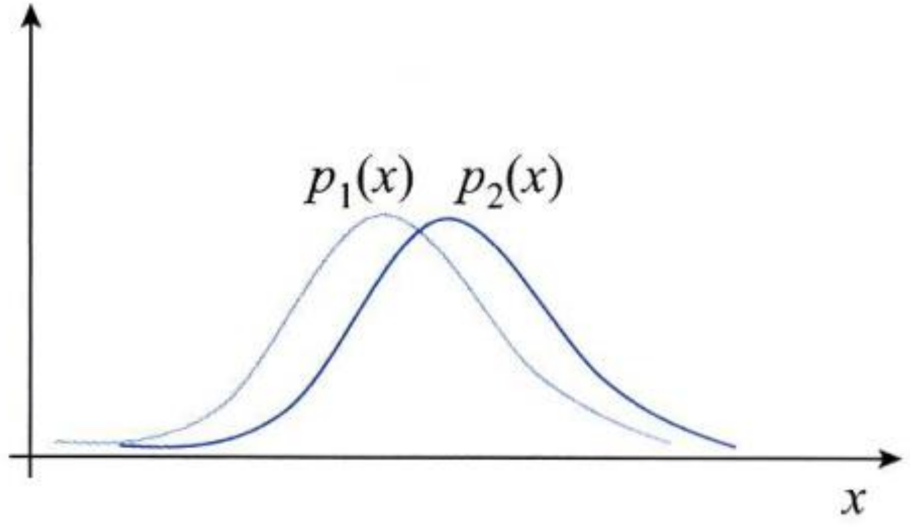
Burnup Measurement (BUMS) versus Reactor Code Comparison

- BUMS and reactor code comparison constitute a powerful tool to accurately measure burnup and improve the accuracy over time (better than current LWRs)
- A statistical sample of pebbles will be selected for more accurate NDA methods or DA. These results will be used to calibrate the BUMS burnup measurements and validate the reactor code predictions for burnup and SNM content.



First deployments – 2030s

Improvements over time



Fully mature technologies

Analysis of Variance – differences between reactors

Analysis of Variance (ANOVA) is a statistical formula used to compare different groups. A range of scenarios use it to determine if there is any difference between the different groups.

For PBR

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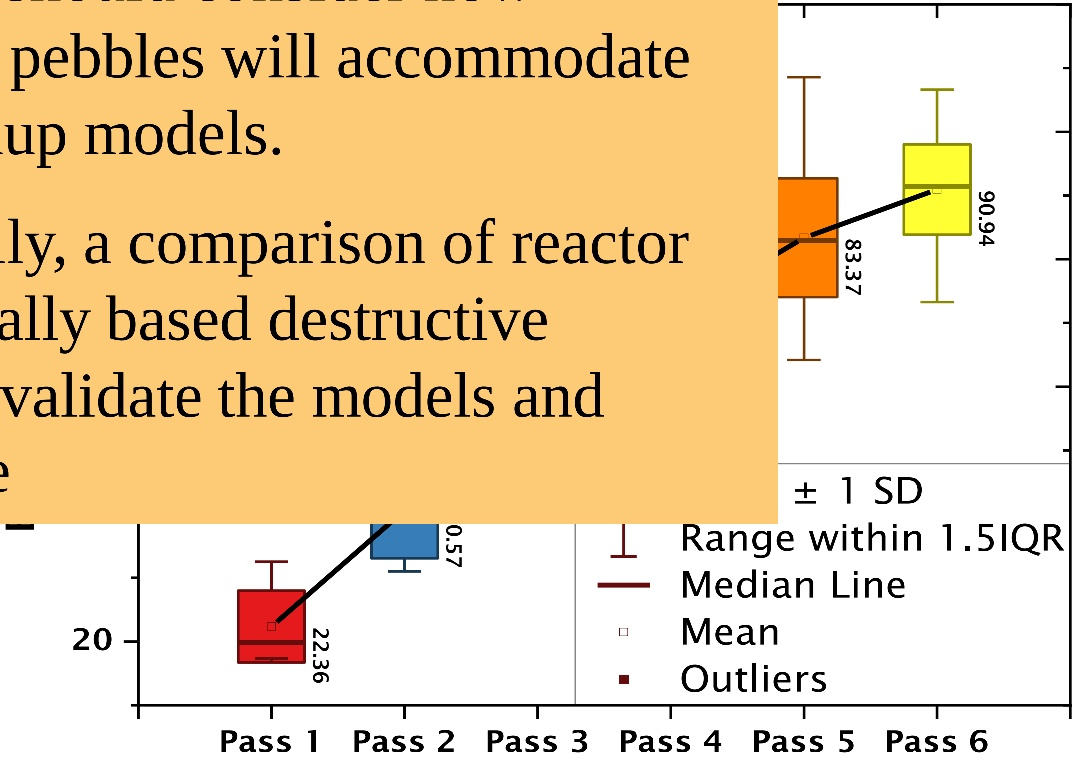
  - Fu
  - Fuel optimization

Recommendation 8: Designers should consider how statistical sampling of spent fuel pebbles will accommodate BUMS and the reactor core burnup models.

Recommendation 9: Additionally, a comparison of reactor models, the BUMS, and statistically based destructive analysis should be performed to validate the models and improve the BUMS performance



Pebble Rounding Errors and MC&A Systems

- Rounding Errors
  - Because of limitations of some MC&A systems, small U/ Pu values per pebble will c
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  - Two commercially available systems were reviewed
  - A full listing of functional specifications was provided including detailed explanation of how it is applied to a facility’s MC&A program.

Recommendation 10: Future PBR owners and operators consider the MC&A software systems that are currently available to determine which one most closely meets their business and operational needs. Some modifications or adaptations may be required for PBRs. These can be performed in-house or outsourced to the software system vendor or a third-party software developer.

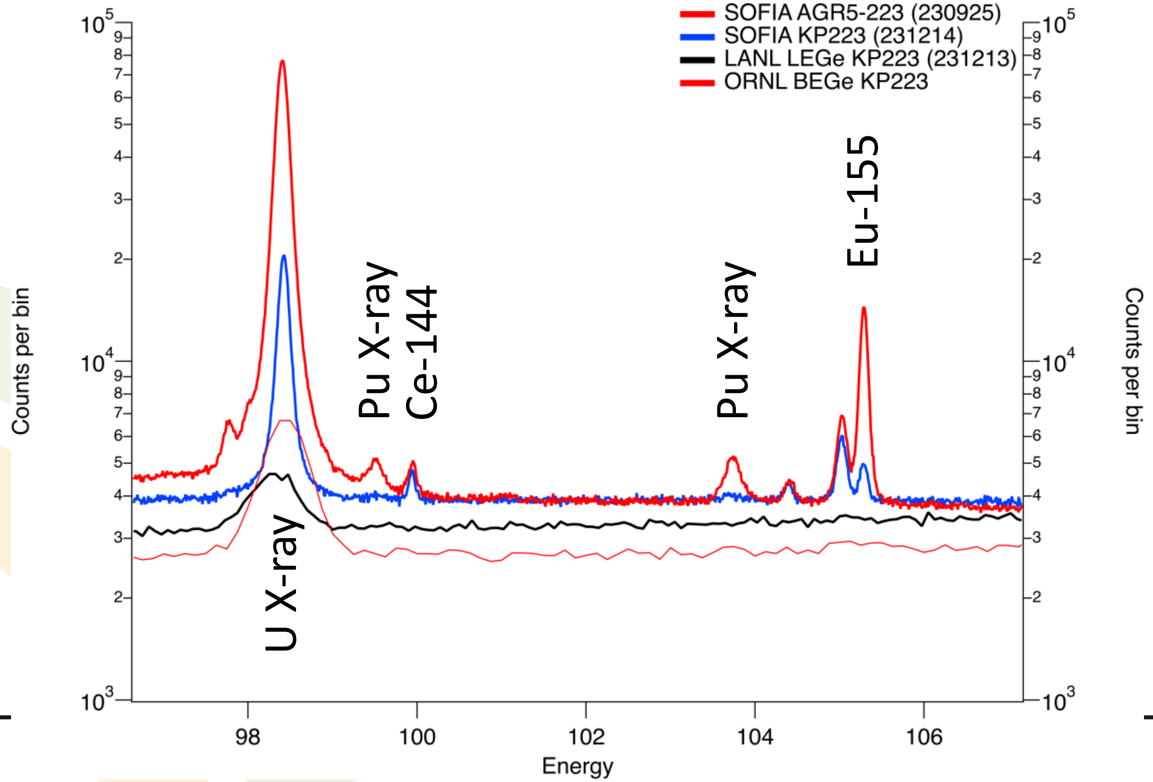
Recommendation 11: If it is determined that the MC&A software will be developed in-house, adequate preparation and understanding of the functional and interface requirements will be needed. Designers should plan accordingly.

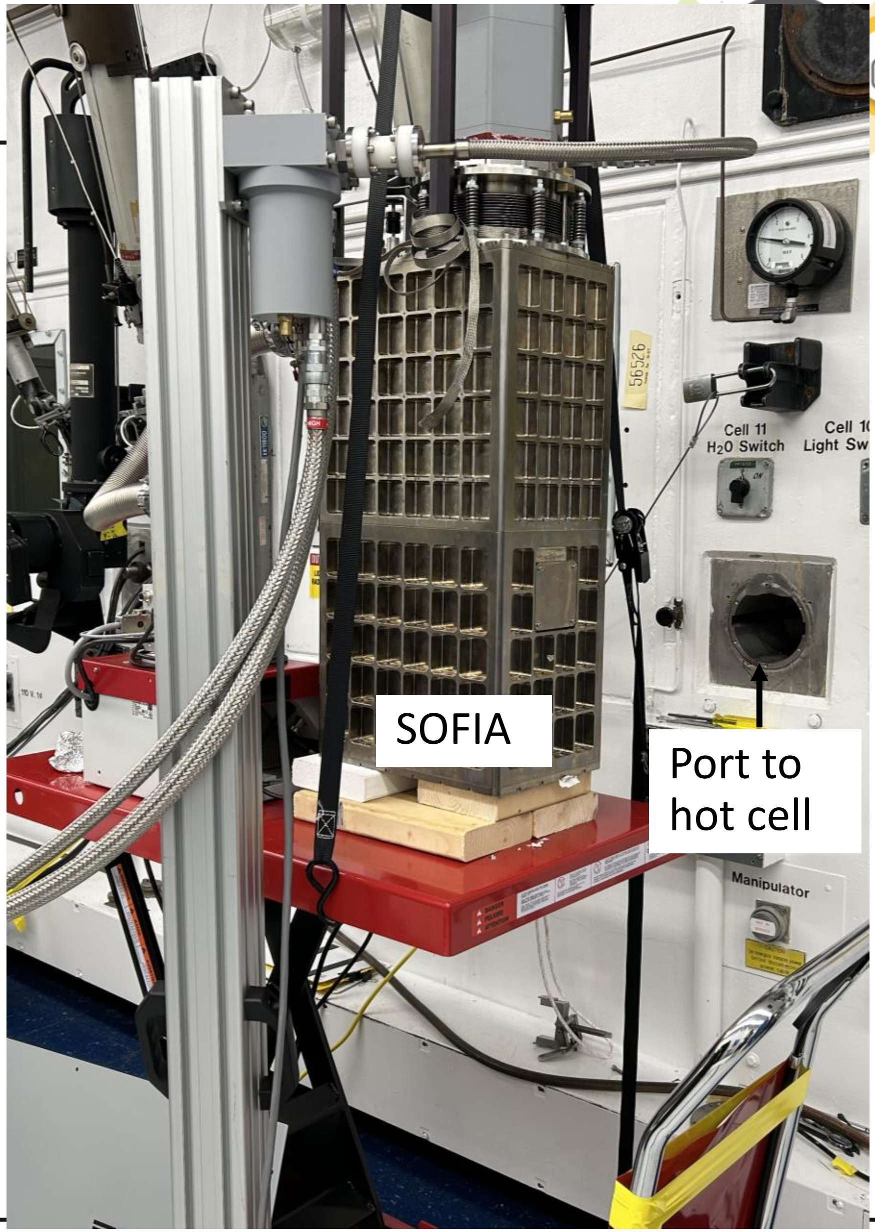
Micro-Calorimetry Measurements at ORNL

- Microcalorimetry
  - Very High Resolution Gamma-Ray Spectrometer
    - Offers 5 times better resolution than the best HPGe detectors
    - Low energy X-rays and gamma Rays
  - Allows identification and quantification of U and Pu for more challenging materials such as irradiated TRISO fuels.
  - Allow determination of 235U enrichment and Pu isotopic abundances with greater precision and accuracy for TRISO materials than other existing gamma-ray based technologies.
- Micro-Calorimetry is a relatively new technique in Non-Destructive Assay and requires some development prior to routine deployments.
  - This work helps to establish the capabilities and development needs for the micro-calorimeters.

Mini fuel measurements in 3525 Fuel Examination Hot Cells

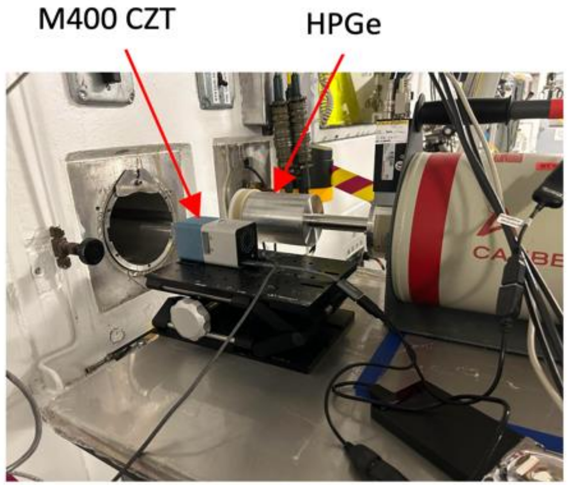
- Measured with SOFIA and HPGe at collimation port to hot cell
- Kairos Power compact 223 measured (14% LEU, 12.43 %FIMA, 22-month cooling time)
- Preliminary analysis performed – burnup measurements possible, but high background from hot cell make it difficult.

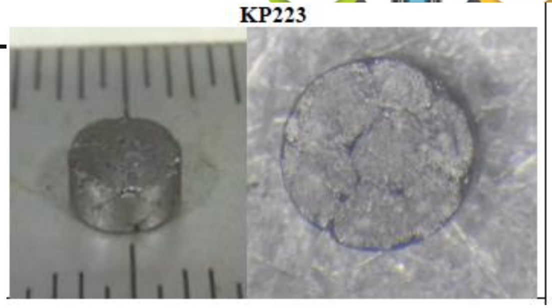




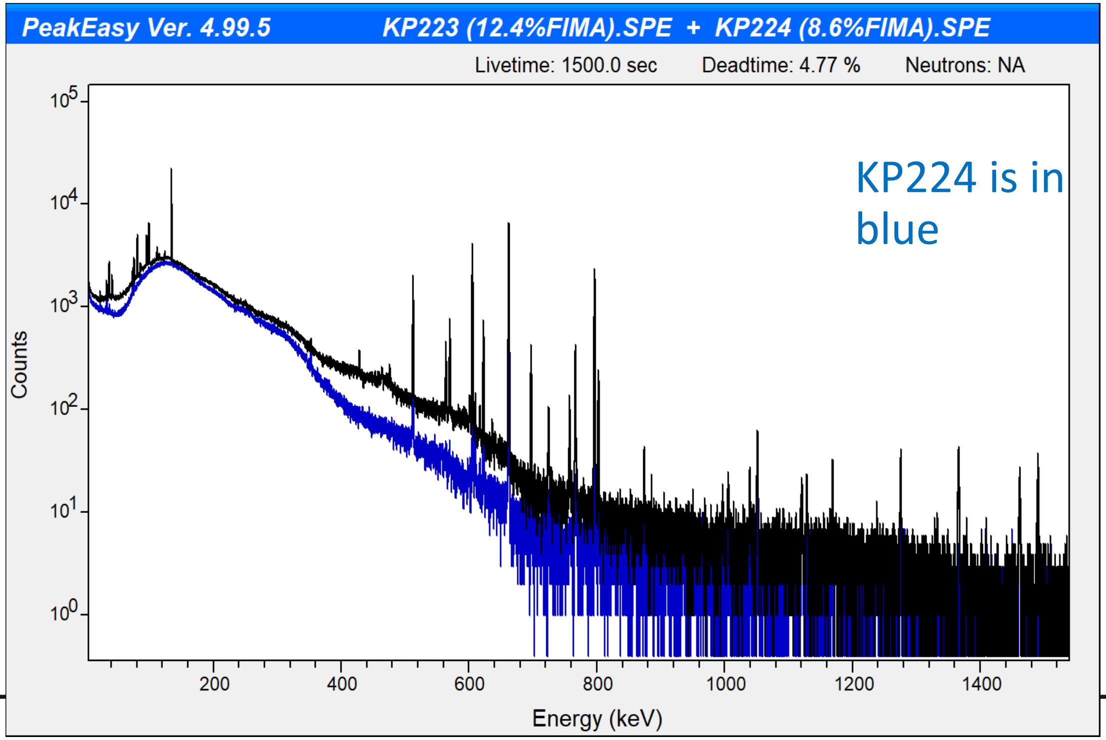
Additional MiniFuel Gamma Measurements in 3525

- Additional MiniFuel measurements were performed under an NNSA/NA-22 safeguards project using a BEGe HPGe and an M400 CZT gamma detector.
- The MiniFuel samples were made available by the Nuclear Science User Facilities program [1].





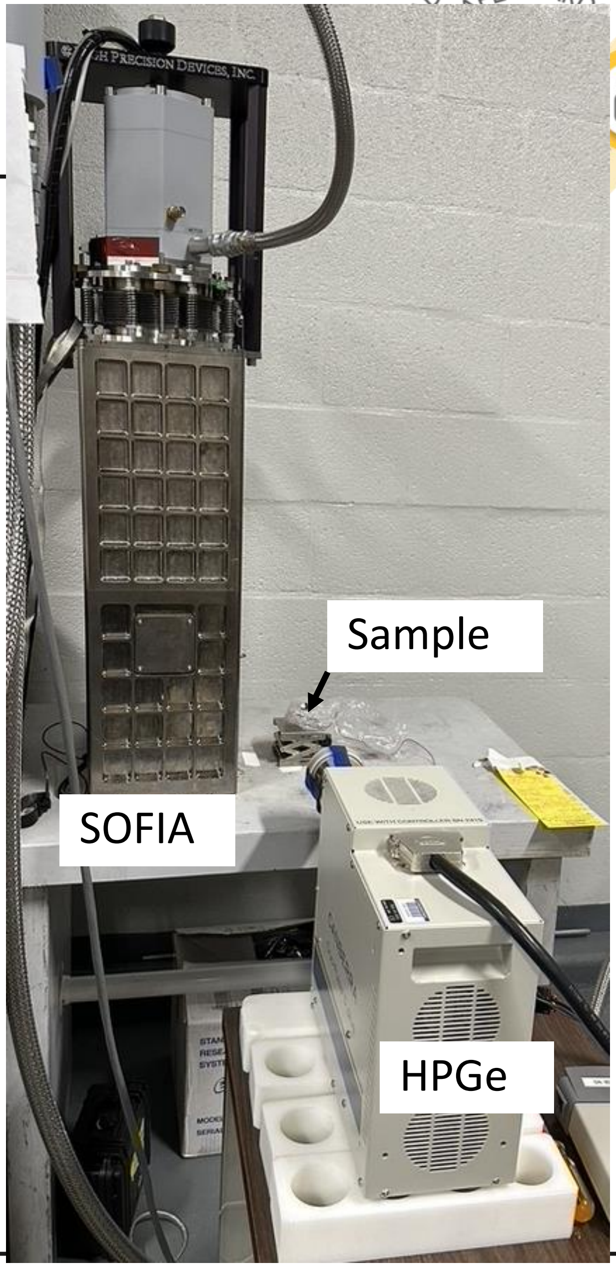
	burnup	Cooling time
Compact ID	%FIMA	months
KP123	11.9	22
KP124	8.6	22
KP125	11.9	22
KP223	12.4	22



[1] A.G. Le Coq, "UCO TRISO MiniFuel FY23 NSUF-Kairos Power Post-Irradiation Examination Status Report", ORNL/TM-2023/2985

SOFIA Measurements at SEL

- Simultaneous measurements SOFIA and high purity germanium detector
- Lower background area – better for detector
- Measurements:
  - 240Pu
  - 233U
  - 2 TRISO particles
  - Metrology mount TRISO particles*
  - Other U/Pu isotopes*
  - NBL cans*



*planned measurements

ADVANCED REACTOR SAFEGUARDS & SECURITY

Uncertainty Quantification of Pebble's Discharge Burnup and Isotopic Inventory: Correlation Matrix

PRESENTED BY Sunil Chirayath

Team Members: Donny Hartanto, Don Kovacic, and Philip Gibbs

May 14-16, 2024

ORNL is managed by UT-Battelle LLC for the US Department of Energy

OAK RIDGE National Laboratory | U.S. DEPARTMENT OF ENERGY

Cleared on 04/29/2024 for Public Release by ORNL/PUB ID 213302

Summary

- This work addressed the major features of PBRs with respect to MC&A
- Pebble counting and statistics will play a major role in MC&A program
- Models must continue to improve, especially for non-equilibrium cases - startup, run-in cores, defueling and refueling of irradiated (used) fuel.
- Statistical sampling and NDA/ DA of irradiate spheres will validate reactor models and improve BUMS calibration and accuracy.
- Operator must balance Type I and Type II errors for economics and safety
- Pebble rounding errors must be taken into consideration in MC&A program
- Operator must select adequate MC&A system based on needs/ requirements
- More work needs to be done based on recommendations of FY23 PBR MC&A report

THANK YOU!